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PRACTICAL HYDROSTATICS

AND

HYDROSTATIC FORMULAS.

BY

E. SHERMAN GOULD,

Mem. Am. Soc. C. E.

Author of "Elements of Water Supply Engineering,"
"Arithmetic of the Steam Engine," "A Primer of
the Calculus," "Sixty Masonry Dams," &c.

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PRACTICAL

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PREFACE.

HYDROSTATICS treats of the physical properties of water at rest, as distinct from HYDRAULICS, which is the science of water in motion.

Of these properties the most important to the engineer is the character and amount of pressure exerted by quiet water against surfaces and bodies in contact with it, and the direction and point of application of such pressure.

These phenomena are governed by a few very simple general laws which suffice to solve all the problems presenting themselves in engineering practice. The most frequently occurring special cases are reducible to formulas of ready application, and when such formulas have been

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PRACTICAL HYDROSTATIC FORMULAS.

GENERAL PRINCIPLES.

1. Matter may exist under two forms: Solid and Fluid. Fluids are again subdivided into non-elastic fluids, or liquids, and elastic fluids, or gases. So we may say more specifically, that matter is divided into three classes; namely, solids, liquids, and gases.

Solids retain their shape by virtue of a property called cohesion, which binds their molecules together as by a cement. Liquids being practically destitute of cohesion must be confined in a vessel, of which they assume the shape, to prevent them from flowing away in downward and lateral directions. The containing vessel may be open at the top, as liquids have no tendency to flow upwards. Gases must be confined in closed vessels, for not only is there no cohesion between their molecules, but on the contrary a force of repulsion, tending to separate them, indefinitely, in all directions, upwards as well as downwards and laterally. In virtue of this property they tend to fill all spaces within which they may be confined, however large. A certain volume of gas may be reduced to a smaller one by pressure, expanding again in virtue of its elasticity, when relieved of the pressure.

Solids and gases, therefore, possess respectively the positive and negative properties of matter, namely, cohesion and repulsion. Liquids occupy a neutral position between the two, their molecules neither cohering to, nor being repelled from each other.

PHYSICAL PROPERTIES OF WATER.

2. Water, the liquid with which hydrostatics and hydrodynamics have to do, may be defined for static and dynamic purposes, as a non-elastic, incompressible fluid, weighing under ordinary conditions about 62.50 lbs. per cubic foot. Strictly speaking, water is not absolutely incompressible, nor is it a perfect fluid, for it possesses an appreciable degree of cohesion, taking the form of *viscosity*. But for the practical purposes of hydrostatics, it may be considered to be as above defined. In hydraulics, the property of viscosity must be taken into consideration, to account for certain otherwise inexplicable phenomena in the flow of water through conduits.

Water is one of several substances found in nature, which is capable of assuming all of the three possible forms, being solid, as ice; liquid, as water; and gaseous, as steam.

Water contracts as its temperature is

lowered down to 39° Fahrenheit, at which temperature it acquires its maximum density. If the temperature is still further lowered, it begins to expand, until it is transformed into ice. A cubic foot of ice weighs only about 58 lbs. as against 62.50 lbs., the weight of a cubic foot of water. Its weight is therefore only about 96% of an equal volume of water. Ice therefore floats in water.

Let a cubic foot of water be frozen to ice in the shape of a solid cube, and let it be placed in a vessel into which it exactly fits. Then, neglecting friction on the sides, it will press against the bottom of the vessel with its full weight of 62.50 lbs., or of $\frac{62.50}{144} = 0.434$ lbs. per sq. in. It will exercise no pressure whatever on the sides of the vessel. Now let the ice be melted into water again. The water will still press upon the bottom with a force of 0.434 lbs. per sq. in., but it will also press against the sides, the amount of pressure diminishing progressively from the bottom, where it is maximum, to the surface of the water where it is nul. Nowhere, however, will it exceed 0.434 lbs. per sq. in. Now suppose the vessel to be closed, and the cubic foot of water converted, by the application of heat, into a cubic foot of steam, at the temperature of 386° Fahrenheit. It will then exercise a pressure of about 195 lbs. above the atmosphere per sq. in. against the bottom, sides and top of the vessel.

TRANSMISSION OF WATER PRESSURE.

3. **Pascal's Law.**—One of the most important physical properties of water, when confined in a closed vessel, is its power to transmit any exterior pressure exercised upon it, equally in all directions. This property, which it shares with the gases, is due to its fluidity.

Fig. 1 represents in vertical section and in plan, an apparatus composed of an irregularly shaped vessel surmounted by a cylinder. In this cylinder a piston, P, is fitted, carrying a weight, *W*. The

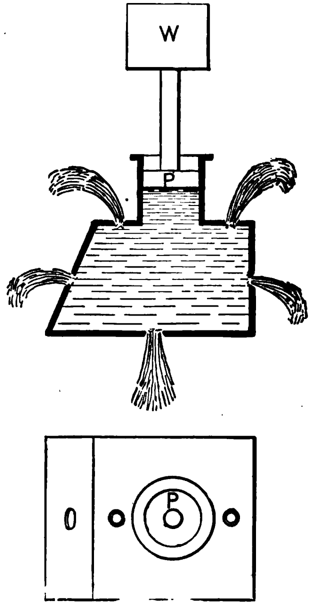

Fig. 1.

vessel is supposed to be full of water, upon the surface of which the piston acts. Suppose the weight, including that of piston and rod, to be 100 lbs. This pressure is transmitted by the water to all parts of the vessel, and if perforations were made in it, as shown in the figure, water would spout out from all of them, the jet being at right angles to the side of the vessel through which it was issuing. The jets at the top would be directed vertically upward, the one at the bottom, vertically downward, the one at the vertical side would be horizontal, and the one in the sloping side would be directed obliquely upward at right angles to the sloping side. These directions refer to the jets as they first issue from the vessel; gravitation would soon overcome all other influence, and the water would fall vertically downward.

If the area of the piston were 5 square inches, it would sustain a pressure of $\frac{100}{5} = 20$ lbs. per sq. in.; and this pressure would be transmitted to every square inch of surface of the vessel, and if the area of each of the perforations were 1 sq. in. and tubes of the same area containing water-tight pistons were fitted to them, it would be necessary to apply a force of 20 lbs. to each piston acting in a direction contrary to that of the water pressure to keep them in place.

This fact will be more readily appreciated if we suppose the cylinder to be prolonged indefinitely, as in Fig. 2, and the piston and weight replaced by a column of water of such height that its weight would be 100 lbs. If now the small perforations were fitted with vertical tubes, as shown in the figure, water would rise to an equal height in all of them, and there would be a pressure of 20 lbs. per sq. in. upon each and every one. The figure is not drawn to scale, but the lower receptacle is supposed to be of such small size relatively that the weight of the water within it may be neglected in estimating the pressure per square inch upon its sides.

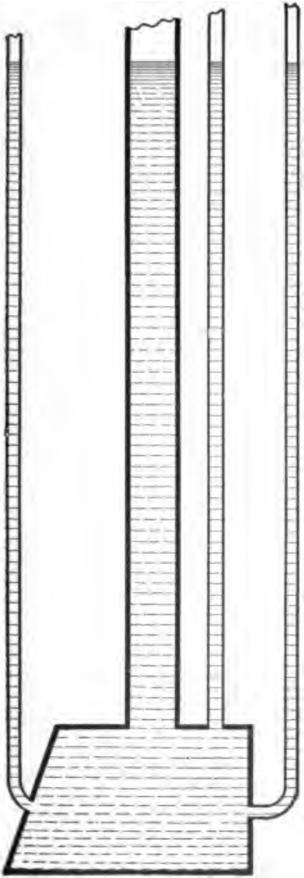

FIG. 2.

As a further illustration, let there be a vessel, of any shape, shown in vertical section by Fig. 3, and let there be any number of openings in the sides of any shape and area. Let these openings be fitted with tubes, turned vertically upward and provided with stop-cocks, *c*, *c′*, *c″*. Let these stop-cocks be open,

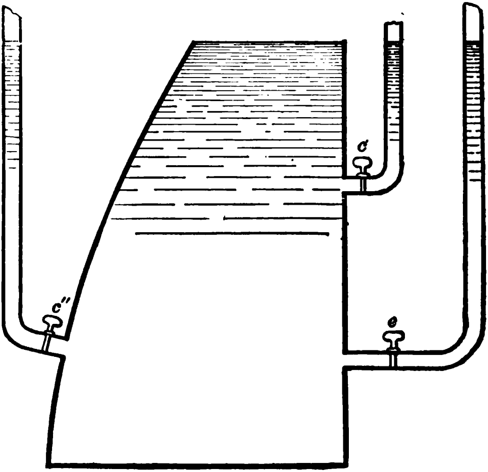

FIG. 3.

and let the whole apparatus be filled with water up to a certain level. Experience teaches us that, as in the previous figure, the water would stand at the same level in the vessel and in all of the tubes, and be in perfect equilibrium throughout.

Let the stop-cocks now be closed. The equilibrium would not be disturbed in any way, and the outward pressure upon the stop-cocks from the water within the vessel would be exactly equal to the inward pressure upon them, from the water in the tubes, so that if the stop-cocks were replaced by pistons free to move in either direction, they would remain stationary, the two opposite pressures exaetly balancing each other.

If now, the stop-cocks being closed, the vessel were emptied of water while the tubes remained full, it is clear that the pressure upon each of them (the stop-cocks) would be equal to its area in square feet multiplied by the height of the column of water in the corresponding tube, multiplied by 62.50 lbs. This therefore would be also the pressure exercised upon the other face of the stopcock from the water in the reservoir.

GENERAL LAW OF HYDROSTATIC PRESSURE.

4. Upon the above facts is founded the fundamental law regarding the action of quiet water against submerged surfaces; a law which is sustained by theory, confirmed by direct experiment, and is expressed as follows:

The total pressure in pounds on any plane submerged surface, of whatever shape, and whether vertical, horizontal or inclined, is equal to its area in square feet multiplied by the vertical distance of its centre of gravity in feet below the surface of the water, and by 62.50. *The direction of this pressure is at right angles to the plane of the surface pressed.*

A few simple illustrations of this law will now be given.

Fig. 4 represents the vertical side of a vessel containing water, filled to the top. What is the pressure upon the rectangular surface, $b\,h$, of which the top and bottom are parallel with the surface of the water, the top being at the depth d below the surface?

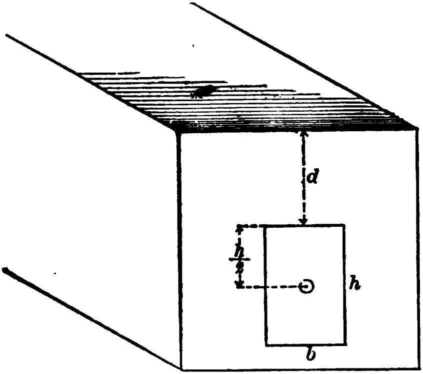

Fig. 4.

The area of the rectangle is $b\,h$, and the centre of gravity is in the centre of the rectangle; its distance below the surface of the water is therefore $a + \frac{h}{2}$. The total pressure, P, on the rectangle by the above law is, therefore:

$$P = b\,h\left(d + \frac{h}{2}\right) 62.50$$

$$P = b\,h\,(2\,d + h)\;31.25. \;.\;.\;(1)$$

Example.—Let $h = 10$ ft.; $b = 5$ ft.; $d = 20$ ft. Find the value of P.

Solution.—
$P = 50 \times 50 \times 31.25 = 78{,}125$ lbs.
Ans.

Since the surface, $b\,h$, is vertical, the direction of this pressure is horizontal.

The area, $b\,h$, in the above example, may be supposed to be that of a rectangular opening in the vertical side of a reservoir containing water. The pressure, P, would then be that upon a sluice-gate covering such orifice.

The formula (1) gives the total pressure upon the whole area, $b\,h$, which, being 50 sq. ft., would give an average pressure of $\frac{78125}{50} = 1562.50$ lbs. per sq. ft. It is evident, however, that there would be a considerable difference between the pressure at the top and at the bottom of the area, and it might be desirable, in a practical case, to know what was the least and greatest pressure per square foot upon the surface.

EXAMPLE.—In the previous example, what is the pressure per square foot at the top and what at the bottom upon the given area?

Solution.—To solve this problem, we consider a surface of 1 sq. ft. at the top and at the bottom of the given rectangle. At the top, we have $b = 1$, $h = 1$, $d = 20.00$. Then, using formula (1), we have, at the top:

$P = (40 + 1)\ 31.25 = 1281.25$ lbs. per sq. ft. *Ans.*

At the bottom, we have $b = 1$, $h = 1$, $d = 20 + 9 = 29$. Then:

$P = 59 \times 31.25 = 1843.75$ lbs. per sq. ft. *Ans.*

PROOF.—In the first of the above examples we found the average pressure per square foot to be 1562.50 lbs. In the last, we found the minimum pressure to be 1281.25 lbs. and the maximum, 1843.75 lbs. Then, since the pressure increases directly and simply with the depth of submersion:

$$\frac{1281.25 + 1843.75}{2} = 1562.50 \text{ lbs.}$$

This proves the correctness of the whole series of examples.

If the top of the rectangle, $b\,h$, in Fig. 4, should reach to the surface of the water in the vessel, as would occur in the case of a sluice-gate closing an open notch in the side of a reservoir, then $d = 0$, and formula (1) reduces to:

$$B = 31.25\, b\, h^2. \quad . \quad . \quad . \quad . \quad (2)$$

This case is the one by far the most generally occurring in practice:

Suppose the submerged surface were in the form of a triangle, Fig. 5, with the base downward and parallel to the surface of the water. Then the area of the triangle is $\frac{b\,h}{2}$, and the distance of the centre of gravity below the surface of the water is $d + \frac{2\,h}{3}$. Then in accordance with the General Law,

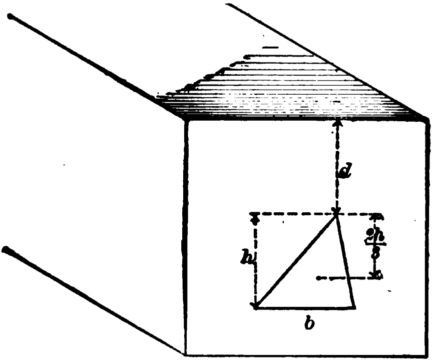

FIG. 5.

$$P = \frac{b\,h}{2}\left(d + \frac{2\,h}{3}\right)62.50$$

$$P = b\,h\,(3\,d + 2\,h)\,10.42. \quad . \quad . \quad (3)$$

If $d = 0$, then

$$P = 20.84\,b\,h^2 \; . \; . \; . \; . \; . \quad (3\text{ bis.})$$

Example.—Let $h=10$, $b=5$, $d=20$, the same as in previous examples. Find the value of P.

Solution.—
$P = 50 \times 80 \times 10.42 = 41680$ lbs. *Ans.*

If the triangle were turned base upward, Fig. 6, parallel with surface of water, then:

$$P = \frac{b\,h}{2}\left(d + \frac{h}{3}\right)62.50$$

$$P = b\,h\,(3\,d + h)\,10.42 \quad . \quad . \quad . \quad (4)$$

If $d = 0$, then

$$P = 10.42\,b\,h^2 \; . \; . \; . \; . \; . \quad (4\text{ bis.})$$

Example.—Reverse the triangle in

previous example, as in Fig. 6, and find P.

Solution.—

$P = 50 \times 70 \times 10.42 = 36470$ lbs. *Ans.*

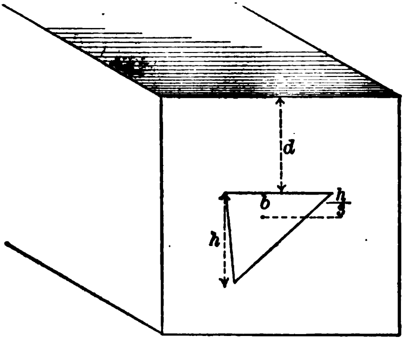

Fig. 6.

Observe that although the area of the triangle is exactly one-half of the rectangle in the first example, when the base is down, the pressure is more than one-half, and when up, less than one-half, that upon the rectangle. The sum of the pressures on the two triangles, however, is equal to the pressure on the rectangle. It is easily seen that this result is due to the difference of depth of centre of gravity of the figures below the surface of the water.

If the figure of the submerged surface is irregular, or irregularly placed, as would be the case of a triangle of which the base was not parallel to the surface of the water, a general formula, would become very complicated, and the area of the figure and its centre of gravity must in each case be found, either graphically or by calculation, and the General Law, page 18, applied. Indeed, the formulas (1) to (4) are only given as being convenient in the special cases to which they apply, but the General Law is the one thing to be faithfully remembered, as it is of universal application, while the formulas may be forgotten with no great loss.

INCLINED SURFACES.

5. If the surface be inclined, as in Fig. 7, the General Law holds, but the direction of the pressure, which is always normal (or at right angles) to the surface, is no longer horizontal, as in the case of a vertical surface, but is inclined, making the same angle with the horizontal that the surface does with the vertical.

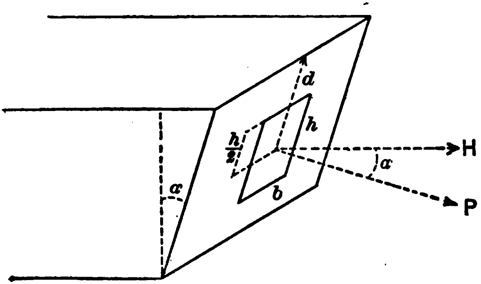

FIG. 7.

Fig. 7 is practically the same as Fig. 4, except that the surface sustaining pressure is inclined at an angle, α, to the vertical. The distance, $d + \frac{h}{2}$, from the surface of the water to the centre of gravity of the submerged rectangle, $b h$, measured along the slope, must be multiplied by cos. α to reduce it to the vertical distance required by the General Law. Formula (1) becomes therefore:

$$P = b h (2 . d + h) \, 31.25 \cos . \alpha . \quad (5)$$

EXAMPLE.—Referring to Fig. 7, let $h = 10$ ft., $b = 5$ ft., $d = 20$ ft., $\alpha = 36°$. Find the value of P.

Solution.—

$$P = 78125 \times 0.809 = 63203 \text{ lbs. } \textit{Ans.}$$

The inclination of the direction of pressure to the horizontal is 36°.

This pressure may be resolved into two components, one an outward horizontal thrust T, and the other a vertical downward pressure, V. See Fig. 8. These components may be obtained graphically or by calculation, thus:

$$T = P \cos. \alpha. \quad \ldots\ldots \quad (6)$$

$$V = P \sin. \alpha. \quad \ldots\ldots \quad (7)$$

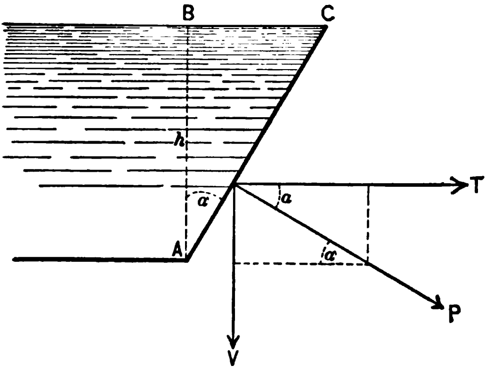

FIG. 8.

From formula (5), we have therefore:

$$T = b\,h\,(2\,d + h)\,31.25 \cos.^2 \alpha. \quad \ldots \quad (8)$$

$$V = b\,h\,(2\,d + h)\,31.25 \cos. \alpha \sin. \alpha. \quad (9)$$

EXAMPLE.—Suppose, in Fig. 7, the top of the rectangle $b\,h$ reaches to the surface of the water, so that $d = 0$. Let $b = 5$, $h = 30$, $\alpha = 30°$. Find T and V.

Solution.—Here $2\,d$ disappears from above formulas, and we have:

$$T = b h^2\ 31.25 \cos.^2 \alpha$$

$$V = b h^2\ 31.25 \cos. \alpha \sin. \alpha.$$

Inserting data:

$$T = 5 \times 900 \times 31.25 \times 0.75 = 105468 \text{ lbs.}$$

Ans.

$$V = 5 \times 900 \times 31.25 \times 0.433 = 60891 \text{ lbs.}$$

Ans.

In the above example, h, measured along the slope being 30 ft. and the angle with the vertical being 30°, the depth of water, measured vertically, with the 25.98 ft., or say 26 ft. Let us then take the following example:

EXAMPLE.—Referring to Fig. 4, let $b = 5$ ft., $h = 26$ ft., and $d = 0$. Find P.

Solution.—Inserting data in formula (2), we have:

$P = 31.25 \times 5 \times 676 = 105625$ lbs. *Ans.*

It will be observed that this is practically the same as the value of T in the previous example, the slight difference being due to the neglect of small decimals.

HORIZONTAL THRUST AND VERTICAL DOWNWARD PRESSURE.

6. This example proves the very important fact, *that the horizontal thrust against a plane surface, retaining a given depth of water, is the same whether the surface be vertical or inclined.*

The vertical downward pressure upon an inclined surface is always that due to the prism of water resting upon it. That is, referring to Fig. 8, it is the triangular prism, A, B, C, resting on the sloping surface A, C. In the example, $A\,B =$ 26 ft. and $B\,C = 15$ ft. Then the weight of the prism is

$$\frac{26 \times 15 \times 62.50 \times 5}{2} = 60937 \text{ lbs.},$$

practically the same as obtained by the

use of formula (9), the difference being due to neglected decimals.

If the side of the vessel or reservoir were inclined in the opposite direction, as shown in section by Fig. 9, the values of *P*, and of *T* and *V*, would be exactly the same as if the inclination were as shown in Figs. 7 and 8, only the direction of *P* and *V*, would be upward instead of downward. *T* would have the same horizontal direction. The law already enunciated, that the horizontal thrust against any plane surface is the same whether the surface be vertical or inclined, *applies in whichever direction the inclination takes place.*

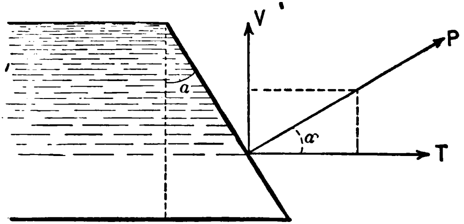

Fig. 9.

In consequence of the General Law that the pressure against any plane surface is equal to the area of the surface multiplied by the depth of water over its centre of gravity, the pressure upon the horizontal flat bottom of a vessel containing water is equal to the area of the bottom multiplied by the depth of water in the vessel, the direction of pressure being, of course, vertically downward.

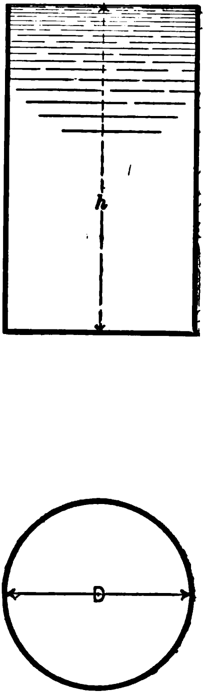

FIG. 10.

EXAMPLE.—Fig. 10 is a vertical section through the axis of a cylindrical vessel filled with water. The diameter, D, of the base is 4 feet, and the depth of water $= h = 12$ feet. What is the total pressure, and what the pressure per square inch on the bottom?

Solution.—The area of the bottom being 12.57 sq. ft. and the height of the cylindrical prism of water above the centre of gravity of the bottom being 12 ft., the total pressure, by the General Law, is $12.57 \times 12 \times 62.50 = 9427.50$ lbs. *Ans.*

The area of the bottom being 1809.55 sq. in., the pressure per square inch is:

$$\frac{9427.50}{1809.55} = 5.21 \text{ lbs. per sq. in. } \textit{Ans.}$$

Example.—In the above example, the height, *h*, of the cylindrical vessel may be supposed to be divided into a series of 12 belts, each one foot high. What is the lateral pressure upon the lowest belt, and what upon the highest, and what is the direction of the line of pressure in both cases?

Solution.—The diameter of the cylinder being 4 ft., the circumference of the circle is 12.57 feet. The area of the belt, 1 ft. high, is, therefore, 12.57 sq. ft. The height of the water-column pressing upon the lowest above its centre of gravity is 11.50 ft. Therefore the total lateral pressure on the belt is:

$12.57 \times 11.50 \times 62.50 = 9034.69$ lbs. *Ans.*

The area of the top belt is the same as the bottom belt, and the water pressure above its centre of gravity is 0.50 ft. The lateral pressure upon the entire upper belt is therefore 392.81 lbs. *Ans.*

The direction of the pressure in both cases is horizontal, and radially outwards from the centre of the cylinder.

Example.—Fig. 11 shows a vertical section through the axis of a vessel in the shape of an inverted truncated cone filled with water. The area of the smaller circle forming the bottom is 1 sq. ft., that of the top, 10 sq. ft. Depth of

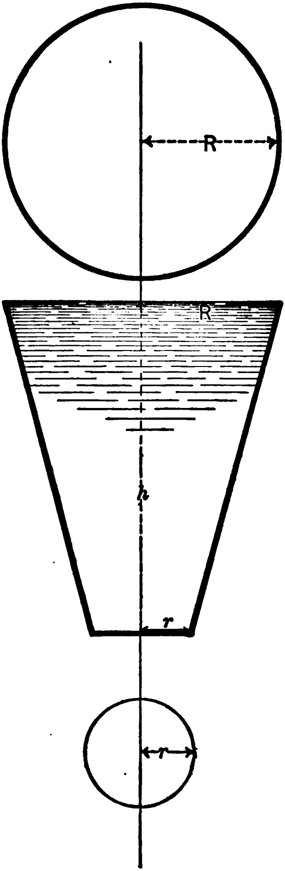

Fig. 11.

water, 15 ft. What is the pressure upon the bottom?

Solution.—

$1 \times 15 \times 62.5 = 937.5$ lbs. *Ans.*

EXAMPLE.—In above example, what is the total downward pressure on the sides of the vessel?

Solution.—If the vessel, filled with water, were suspended by a spring balance, or placed upon a platform scales, the entire downward pressure of the water would be shown to be the weight of the whole, less the weight of the vessel; that is to say, would be the actual weight of the body of water contained in the vessel. In this case, the whole weight of the contained water is, by a well-known formula:

$$(1 + 10 + \sqrt{10}) \frac{15}{3} \times 62.5 = 4425 \text{ lbs.}$$

The pressure on the bottom we have just seen to be 937.5 lbs.; therefore the pressure on the sides is:

$4425 - 937.5 = 3487.5$ lbs. *Ans.*

NOTE.—The total pressure normal to the slant surface of the truncated cone can be obtained by multiplying the total downward pressure, as above, by the cosecant of the angle which the slant height makes with the vertical.

EXAMPLE.—What is the total pressure on the slant surface in the above example?

Solution.—The area of the circle forming the large end being 10 sq. ft., the radius of the circle is 1.782 ft., and the area of the circle forming the small end being 1 sq. ft., its radius is 0.564 ft. The difference between the two, divided by the height, gives the tangent of the desired angle, thus:

$$\frac{1.782 - 0.564}{15} = 0.081 = \text{tang. } 4^\circ\, 39'.$$

The cosecant of 4° 39′ = 12.34, therefore the total pressure on the sides of the vessel is

$$3487.5 \times 12.34 = 43036 \text{ lbs. } \textit{Ans.}$$

The direction of this pressure is radially outward and normal to the slant sides of the vessel.

EXAMPLE.—Fig. 12 shows same figure as above, only reversed, with the large area down. Dimensions being the same, what is the pressure on the bottom?

Solution.—

$10 \times 15 \times 62.5 = 9375$ lbs. *Ans.*

EXAMPLE.—What is the total upward pressure against the sides of the above vessel?

Solution.—The total *downward* pressure of the water due to its weight would be shown on a platform scale te be, as before, 4425 lbs. But the pressure on the bottom, tending to burst it out, we have just seen to be 9375 lbs. Consequently the upward pressure neutralizing a portion of this pressure on the bottom must be:

$9375 - 4425 = 4950$ lbs. *Ans.*

The total pressure on the sides, normal

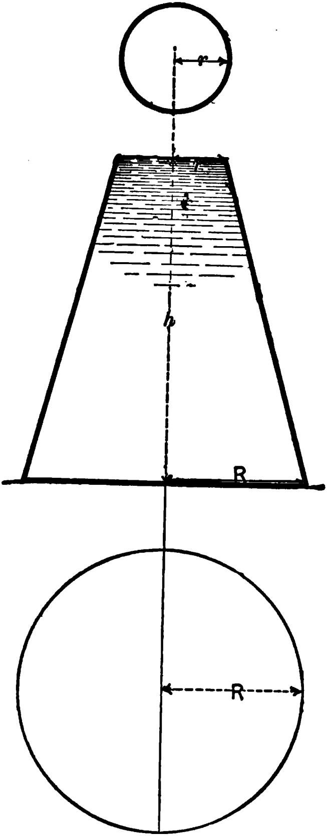

Fig. 12.

to their direction, is found as above, by multiplication by the cosecant of the angle of slant. Thus:

$$4950 \times 12.34 = 61083 \text{ lbs.}$$

It might seem as if this value should be the same as that just found for the inverted vessel, only directed upward instead of downward. The reason for its being greater is that the centre of gravity of the slant surface sustaining pressure is lower in this case than in the former, and the General Law applies, which tells us that the total pressure upon any plane surface is equal to the area of that surface multiplied by the distance of its centre of gravity below the surface of the water pressing against it. In the case of a cone, or a truncated cone, the slant surface may be developed into a plane, which brings it within thc scope of the General Law.

7. The existence of this upward pressure explains the otherwise puzzling fact that the pressure on the bottom of a vessel like that shown in Fig. 12, is greater than the whole weight of the water which it contains. The pressure of confined gases upon the vessels containing them, affords an easily recognised parallel. For instance, if the water contained in the vessel shown in Fig. 12, which would weigh, as we have seen, 4425 lbs., were replaced by an equal volume of steam at the temperature of 386° Fahr., it would exercise a pressure of 195 lbs. above the atmosphere on every square inch of surface. As the bottom in Fig. 12 contains 1440 sq. in., the total downward pressure would be 280800 lbs., or nearly 900 times as much as the weight of the steam in the vessel, which is only that of the water from which the steam is formed.

It will be well to pursue this subject a little further, by means of another example.

EXAMPLE.—Let Fig. 13 represent a vertical section through a vessel containing water, composed of two cylinders,

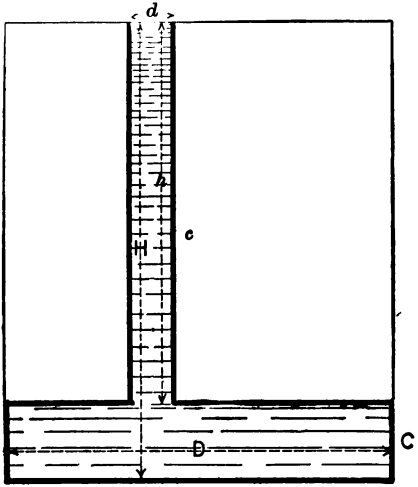

FIG. 13.

one, C, of diameter $=D$, and the other, c, of diameter $= d$, superposed upon the larger one. Let $d = 1$ ft., $D = 10$ ft., $H = 12$ ft., $h = 11$ ft. What is the pressure upon the bottom of the lower cylinder, *C*?

Solution.—
$78.54 \times 12 \times 62.50 = 58905.00$ lbs. *Ans.*

Example.—In the above example, what is total weight of water contained in the whole vessel?

Solution.—
$(78.54 + 0.785 \times 11)\ 62.50 = 5448.44$ lbs. *Ans.*

Example.—In the above example, what is the upward pressure upon the top of the lower cylinder?

Solution.—
$(78.54 - 0.785)\ 11 \times 62.50 = 53456.56$ lbs. *Ans.*

Proof.—The total downward pressure on the bottom of the large cylinder, less the upward pressure on the annular top, should be equal to the total weight of water in the apparatus. Thus:

$58905.00 - 53456.56 = 5448.44$ lbs.

This result proves all the work to be correct.

Suppose now that the diameter of the upper cylinder, c, be greatly decreased; for instance, let $d = 0.10$ ft. The pressure upon the bottom of the cylinder, C, would remain precisely the same, the total weight of water contained in the apparatus would be diminished, and the upward pressure against the annular top of cylinder C' proportionately increased. The pressure upon the bottom of the large cylinder is therefore the same, whether the full diameter, D, be carried to the full height, h, as shown by the dotted lines in the figure, or whether the diameter, d, of the upper cylinder be greatly reduced as in the example, provided d be not so small as to introduce the effect of *capillarity.*

It is hard for the mind unfamiliar with these subjects to realize that such heavy pressures can be exercised by such relatively small volumes of water, and it is probable that the fact would not generally commend itself to the understanding, were it not fully confirmed by actual experiment.

Let us see how the facts, arrived at by calculation, may be proved experimentally.

Let *C*, Fig. 14, represent a cylindrical vessel of diameter, *D*, in which a piston, *P*, *P*, of the same diameter is fitted. Let the piston rod, *t*, be a tube of inside diameter, *d*, and of indefinite length, *h*. This apparatus is practically the same as that shown in Fig. 13, except that some of its parts are movable.

If water were now poured in by the tube, *t*, an upward pressure would be exercised upon the bottom of the piston, *P*, *P*, which would rise, unless kept down by the weights *W*, *W*. To avoid unnecessary calculation, suppose the area of the piston to be 10 sq. ft. and the inside area of the hollow piston rod, *t*, to be 0.10 sq. ft. Let the weights, *W*, *W*, be 1000 lbs. each, making a total weight of 2000 lbs., or rather, let the weight be such that the combined weights of *W*, *W*, and the piston and rod reach 2000 lbs.

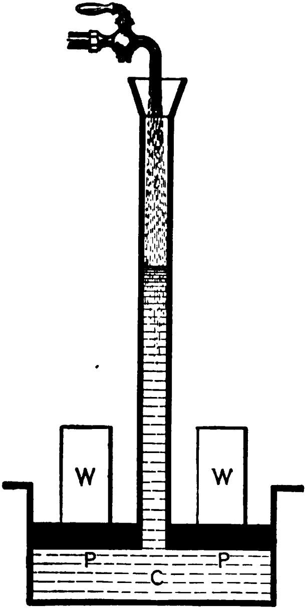

FIG. 14.

How high a column of water must stand in the tube, *t*, to keep the apparatus in equilibrium, so that the piston neither rises under the water pressure, nor falls under that of the weights, the friction of the piston being neglected?

There must be an upward pressure under the piston equal to 2000 lbs. Let x = the height of water in the tube to produce this pressure. Then

$$10x \times 62.5 = 2000$$

$$x = 3.20 \text{ ft.}$$

Therefore a column of water in the small tube, weighing only $3.20 \times 0.10 \times 62.50 = 20$ lbs., has sufficed to counterbalance a weight of 2000 lbs., the weights being in direct proportion to the areas of the two cylinders.

Now suppose water sufficient to fill the small tube to a double height, or 6.40 ft., were poured in. The upward pressure would be doubled and the piston and the weights would be raised, and the level of the water in the tube would be lowered, until it stood again at the height, 3.20 ft., necessary to produce equilibrium. How high would the piston have risen when equilibrium was restored?

The area of the tube, t, being 0.10 sq. ft., the volume of water introduced into the apparatus is $0.10 \times 3.20 = 0.32$ cu. ft. This must enter into the large cylinder, C, of which the area is 10 sq. ft. The rise, x, must then be:

$$x = \frac{0.32}{10} = 0.032 \text{ ft.}$$

The weight of the water introduced into the tube is $0.32 \times 62.5 = 20$ lbs., as we have already seen. It descended 3.20 ft., so that its "work" was $20 \times 3.20 = 64$ foot-pounds. On the other hand, the weight of 2000 lbs. has been moved through 0.032 ft. Its work, therefore, was $2000 \times 0.032 = 64$ foot-pounds, or just equal to the work of the water introduced into the tube, in producing equilibrium.

This phenomenon of a small volume of water raising, or balancing a much greater weight than its own, which has sometimes been called "the hydrostatic paradox," is thus shown to be justified by dynamic principles, and has been moreover demonstrated, time and again, both by laboratory experiments and pieces of machinery in actual use.

HYDRAULIC PRESS.

8. Of these latter, the Hydraulic Press is the most striking example. The principle of this machine will be understood by reference to Fig. 15, which represents an apparatus consisting of two cylinders fitted with plungers, one large, *b*, and one small, *a*, and connected together by the mass of water contained in the body of the apparatus. If a weight, or a force represented by a weight, be applied to the small plunger, *a*, it is moved downward, forcing water from the small cylinder into the large one, and thereby raising the large plunger, *b*. Suppose the sectional area of the small plunger to be

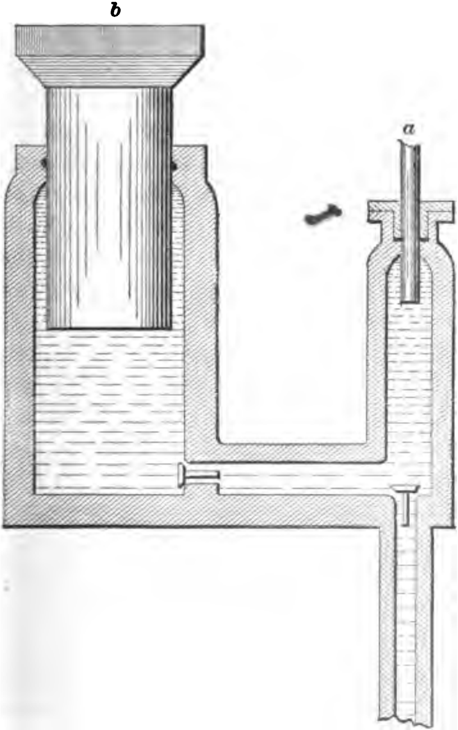

Fig. 15.

1 sq. in., and a force of 100 lbs. be applied to it. Then a pressure of 100 lbs. per sq. in. is exerted in every direction through the mass of water, and if the sectional area of the large plunger be 100 sq. in., it sustains an upward pressure of $100 \times 100 = 10000$ lbs., and would raise, or balance that weight if placed upon it. It is clear that the greater the difference in area of the two plungers, the greater will be the pressure exerted upon the larger by a force applied to the smaller. Suppose the area of the large plunger to be 1000 sq. in., the area of the small one being still 1 sq. in. Then a force of 100 lbs. on the small plunger balances one of 100000 lbs. on the larger one. This is in full accordance with Descartes's law of virtual velocities, that what is gained in power is lost in speed, for the smaller the actuating plunger, *a*, the greater the distance it must travel to raise the larger one a given distance, and the force applied to one, multiplied by the distance it

travels, will always be equal to the weight upon the other, multiplied by the distance which it travels.

EXAMPLE.—In Fig. 15, let the sectional area of the smaller plunger be 1 sq. in. and that of the larger be 100 sq. in. If the small plunger be forced down 1 ft., how much will the large one be raised?

Solution.—The small plunger will displace 12 cu. in. of water, which will be forced into the larger cylinder, the plunger of which will rise to make room for it. The area of the latter being 100 sq. in., it will rise $\frac{12}{100} = 0.12$ in. *Ans.*

EXAMPLE.—If the area of the larger plunger be 1000 sq. in., how far will it be raised, the other conditions being as in preceding example?

Solution.— $\frac{12}{1000} = 0.012$. *Ans.*

In the practical application of this

principle to the hydraulic press when used for the compression of bales of goods, the motion being very slow, and the resistance at the commencement of the compression very slight, there should be two pumps attached to the press, one of larger diameter, to bring the pressure to bear rapidly, and a smaller one, as above, for the final and more intense pressure required.

SPECIAL CASES OF HYDROSTATIC PRESSURE.

9. The above examples cover all—and probably more than all—the cases likely to occur in practice regarding the pressure of water against surfaces. Should others present themselves either as practical questions, or as matters of curiosity, they may all be solved by the application of the General Law, given on page 18. This law, it will be observed, is confined by its enunciation to plane surfaces, but as curved surfaces may be considered as made up of an infinite number of planes, the law may be extended to embrace curved surfaces as well.

Thus, if it were required to find the total pressure upon a vessel in the shape of a hollow half sphere filled with water, the radius of the sphere being r, we could still apply the General Law. For the area of the surface is $2 \pi r^2$, and the distance of its centre of gravity from top or bottom is $\frac{r}{2}$. Therefore, the pressure, P, is:

$$P = \pi r^3 \, 62.50 = 196.25 \, r^3 \quad . \; . \quad (10)$$

and it extends radially in all directions. The total downward pressure is the weight of the contained water.

Example.—A semi-circular caldron, 3 ft. interior diameter, is filled with water. What is the total pressure, P, against the interior surface, and what the total pressure, V, vertically downward?

Solution.—

$P = 196.25 \times 3.375 = 662.34$ lbs. *Ans.*

$V = 2.095 \times 2.25 \times 62.5 = 294.61$ lbs. *Ans.*

If there should be water pressure on both sides of a submerged surface, the actual pressure upon it is the difference between the two. Thus:

Let Fig. 16 represent a vertical section through a diaphragm containing a rectangular orifice of height, *h*, and breadth, *b*, closed by a sliding gate, the depth of water over the top of the orifice being *d* on one side, and *d′* on the

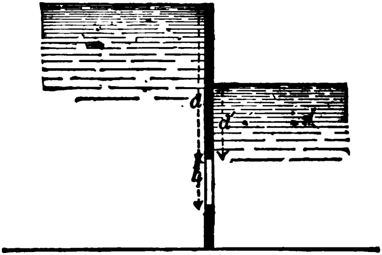

FIG. 16.

other. What is the total pressure upon the gate?

By formula (1) the pressure on one side is:

$$P = b\,h\,(2\,d + h)\,31.25,$$

and on the other:

$$P' = b\,h\,(2\,d' + h)\,31.25.$$

The total pressure, P'', is then

$$P'' = P - P'$$

$$P'' = b\,h(2\,d + h)31.25 - b\,h(2\,d' + h)31.25$$
$$= bh\,(d - d')\,62.50 \text{ lbs.}$$

Example.—$d = 10$; $d' = 5$; $h = 6$; $b = 2$, all in feet. Find P'' in pounds.

Solution.—
$P'' = 12 \times 5 \times 62.50 = 3750$ lbs. *Ans.*

EXAMPLES FOR PRACTICE.

1. A vessel, as shown in Fig. 1, is fitted with a piston, *P*, 10 inches in diameter, which sustains a weight, *W*, including its own, of 5792 lbs. The sloping side has a rectangular orifice in it, $2\frac{1}{8}$ in. in height, and $1\frac{3}{16}$ in. in breadth. If the orifice were closed by a steel plate riveted over it, what pressure would the plate sustain from the weight, *W*?
186 lbs. *Ans.*

2. Referring to Fig. 2, let the diameter of the largest tube be 7 in. and the height of water in it $17\frac{1}{2}$ ft. Let the diameter of the orifice in the top of the receptacle be 2 in. If this orifice were closed by a plate on the outside instead of the tube, what would be the pressure against the plate? Is it necessary in order to solve this example, that the diameter of the large tube be known?
23.77 lbs. *Ans.*
No. *Ans.*

3. A rectangular opening, 4 ft. 8 in. high, and 3 ft. 2 in. wide, in the vertical side of a vessel containing water, has its top side parallel with the surface of the water, and at a depth of 76 in. below it. If the orifice be closed with a sliding gate, what is the pressure against the gate?

8004.29 lbs. *Ans.*

4. In the above example, suppose the opening to extend to the surface of the water. What would then be the pressure?

11974 lbs. *Ans.*

5. A right angled triangle, 5 ft. high with a base of 3 ft. in the vertical side of a vessel containing water, is immersed right angle down, to a depth of 7 ft. above the apex. The base makes an angle of 14° with the surface of the water. What is the pressure upon the triangular surface?

4687.5 lbs. *Ans.*

6. In the side of a receptacle containing water, as shown in Figs. 7 and 8, sloping at an angle of 15° with the vertical, let there be a rectangular opening, 10 ft. in height and 5 ft. in width, the top not parallel with the surface of the water, but inclined at an angle of 5° 15′ to it. Let the surface of the water be 6 ft. above the upper corner of the rectangle, all distances being measured on the slope, as in Fig. 7. If a steel plate be riveted over the opening, on the outside, what is the pressure, P, against the plate, what the horizontal thrust, T, against it, and what the vertical downward pressure?

$P =$ 33812.5 lbs. *Ans.*
$T =$ 32662.9 " *Ans.*
$V =$ 8757.4 " *Ans.*

7. A vessel in the shape of a symmetrical 4-sided pyramid with the base up is filled with water. The base is a rectangle 6 ft. by 8 ft., and the perpendicular height of the pyramid is 12 ft. What is the pressure, *P*, the horizontal thrust, *T*, and the vertical pressure, *V*, on each side?

$P = 12370$ lbs. on each long side.
$= 9488$ " " short "
$T = 12000$ " " long "
$= 9000$ " " short "
$V = 3000$ " " long "
$= 3000$ " " short "
Ans.

8. In an apparatus, such as is shown in Fig. 14, the diameter of the cylinder, *C*, is 48 in., and that of the tube, *t*, 3 in. There is no water in the apparatus. A man, weighing with the movable piston 200 lbs., stands in the place of the weights, *W*, *W*, and lets water from the faucet run into the tube. How many U. S. gallons of water must he let in in order to raise the piston and himself 6 inches, neglecting friction, and how high will water stand in the tube?

47.22 gals. *Ans.*
0.2556 ft. *Ans.*

9. The small plunger of an hydraulic press has a diameter of 1 inch and a stroke of 8 inches. The large plunger has a diameter of 12 inches. How many strokes of the small plunger will be necessary to raise the large one 1 inch?

18. *Ans.*

CENTRE OF PRESSURE.

10. THE CENTRE OF PRESSURE is the point at which the total pressure upon a submerged surface, determined as in the preceding article, may be considered as being concentrated. That is, it is the point in such surface through which the resultant of all pressures upon it passes, and at which a counter pressure of equal intensity and contrary direction would just balance it.

Unless the surface is horizontal, as in the case of the flat bottom of a vessel containing water, *the centre of pressure is always below the centre of gravity of the surface.* The two approach each other, however, as the depth of immersion (*d*, in Figs. 4, 6 and 7) increases, and at a great depth would nearly coincide. They are farthest apart when $d = 0$. Why this is so will be seen later.

Referring to Fig. 17, which is another view of Fig. 4, it is evident that the water pressure at the top of the rectangular surface is that due to a depth of water $= d$, and at the bottom to one of $d + h$. These pressures, as we have already seen, are exercised at right angles to the surface pressed upon, so we may represent graphically the mass of water pressing against the surface $b\,h$, by lay-

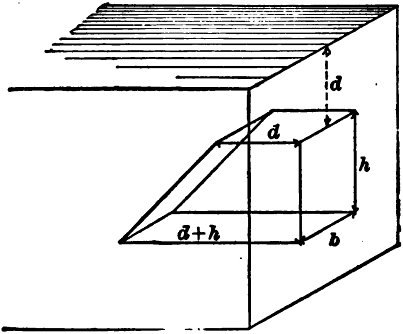

FIG. 17.

ing off the lines *d* and $d + h$ at right angles to the surface, and completing the trapezoidal prism as shown in Fig. 18. Now turn the figure around so that the surface, *b h*, shall be horizontal, and the

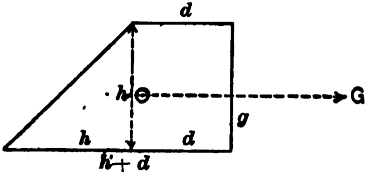

FIG. 18.

lines *d* and $d + h$ vertical, and the pressure upon the surface is precisely as if a similar mass of any substance of the same density as water were resting upon it.

That this is true is easily proved; the volume, *Q*, of the prismoid *b*, *h*, *d*, $d + h$, is:

$$Q = \frac{b\,h}{2}\,(2\,d + h),$$

and its weight, *W*, is:

$$W = b\,h\,(2\,d + h)\;31.25.$$

But this is precisely the pressure, *P*, already given by formula (1).

GENERAL LAW FOR THE CENTRE OF PRESSURE.

11. The resultant of the pressure of this mass of water (as of any other ponderable substance) upon the surface passes through its centre of gravity. Hence the general law of the centre of pressure is, *that it is on the line passing through the centre of gravity of the prism of water pressing against the surface, and is at the point where this line intersects said surface.*

In the case shown in Fig. 17 the centre of gravity of the prism is easily found, for we need only find that of the trapezoid shown in Fig. 18. By the well-known and easily verified rules for finding the centre of gravity of a trapezoid, the height, g, above the base at which the line, G, passes through the centre of gravity of the trapezoid is:

$$g = \frac{h}{3}\left(\frac{3\,d + h}{2\,d + h}\right).$$

It has already been stated that the centre of pressure more nearly approaches the centre of gravity of the surface pressed as the depth of immersion, d, increases. If in the above equation, d increases indefinitely, h becomes insignificant in comparison, and therefore disappears from between the brackets. The equation then becomes:

$$g = \frac{h}{3} \times \frac{3}{2} = \frac{h}{2}.$$

But this is the height of the centre of gravity of the rectangle $b\,h$, above the base. Indeed, a mere inspection of Fig. 18 shows that the trapezoid, being made up of the rectangle $d\,h$ and the triangle h, h, its centre of gravity must always be lower than that of the rectangular portion, but that it is less so the greater the value of d in comparison with that of h.

Should $d = 0$; that is, if the rectangular surface $b\,h$ extends to the surface of the water, the above equation becomes:

$$g = \frac{h}{3}.$$

The latter case is at once the most simple and the most common in practice.

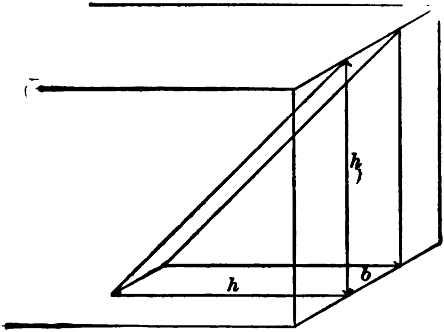

FIG. 19.

It is easily verified by constructing the figure shown in Fig. 19.

EXAMPLE.—Referring to Fig. 19, let $h = 30$ ft., $b = 5$. What is the weight,

P, of the prism of water pressing against the surface $b\,h$?

Solution.—The area of the triangle h, h, is $\frac{30 \times 30}{2} = 450$ sq. ft., which multiplied by 5 gives the number of cubic feet in the prism h, h, b, and this multiplied by 62.50 gives the weight of the prism. Thus:

$$P = \frac{30 \times 30}{2} \times 5 \times 62.50 = 140625 \text{ lbs.}$$

Ans.

Check this value by formula (2).

Example.—At what height above the base does the line passing through the centre of gravity of the prism of water in the above example cut the surface $b\,h$?

Solution.—The centre of gravity of the triangle, $h\,h$, is at the height, $\frac{h}{3}$, above the base. Therefore:

$$g = \frac{30}{3} = 10 \text{ ft.} \quad \textit{Ans.}$$

CENTRE OF PRESSURE ON INCLINED SURFACES.

12. If the surface be inclined, as in Fig. 7, the position of the centre of pressure in relation to the base of the surface is the same as for a vertical surface. Fig. 20 is a vertical section through the inclined surface shown in Fig. 7. In this case we construct the same trapezoid, only the sides d' and $d' + h'$ are obtained by multiplying d and h by the cosine of the angle α, which the surface makes with the vertical, as the vertical depths of water are required.

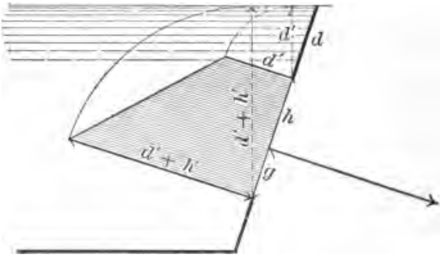

FIG. 20.

Example.—Referring to Figs. 7 and 20, let $h = 10$ ft., $b = 5$ ft., $d = 20$ ft., and $\alpha = 36°$. What is the pressure, P, as obtained from the figures, exercised against the surface $b\,h$?

Solution.—Cos. 36° = 0.809. Therefore $d' = 20 \times 0.809 = 16.18$; $h' = 10 \times 0.809 = 8.09$. Then the prism of water contains:

$$\frac{16.18 + 24.27}{2} \times 10 \times 5 = 1011.25 \text{ cu. ft.},$$

and the weight, or pressure, P, is:

$$P = 1011.70 \times 62.50 = 63203. \quad \textit{Ans.}$$

This is the same, with the slight difference due to neglect of small decimals, as that already given in connection with formula (5).

The line passing through the centre of gravity of the prism, is evidently at the same height from the base of the surface as if the surface were vertical, although its direction is oblique instead of horizontal.

There has been no difficulty in ascertaining the centre of gravity of the simple prisms involved so far, but it becomes more complicated when surfaces like those shown in Figs. 5 and 6 are under consideration, and in all cases the processes of solid geometry require more or less pains in their application. A general formula will therefore be now presented, applicable to all rectangles, triangles and trapezoids having horizontal bases.

GENERAL FORMULA.

13. Let Fig. 21 represent the front view of a trapezoidal surface forming part of the vertical side of a vessel containing water to the height, d, above the top of the trapezoid under consideration. Then, g being the height of the centre of gravity, G, of the figure, we have the general formula:

$$g = \frac{h^2\,(b+b') + 2\,h\,d\,(b+2\,b')}{2\,h\,(2\,b+b') + 6\,d\,(b+b')} \quad . \; . \quad (11)$$

If $d = 0$:

$$g = \frac{h}{2}\left(\frac{b + b'}{2\,b + b'}\right). \quad \text{(11 bis.)}$$

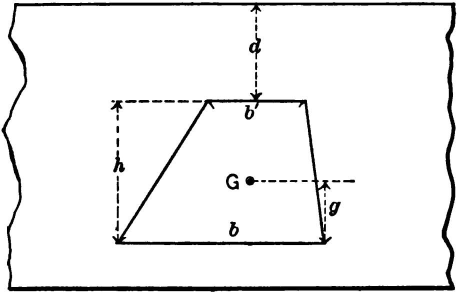

FIG. 21.

Let us now establish a series of special formulas from the above general one, repeating those already given, as follows:

If a surface be a rectangle, then $b = b'$, and the general formula (11) becomes:

$$g = \frac{2\,h^2 b + 6\,h\,d\,b}{6\,h\,b + 12\,d\,b}$$

$$g = \frac{h}{3}\left(\frac{h + 3\,d}{h + 2\,d}\right) \quad \ldots\ldots \quad (12)$$

When $d = 0$, formula (12) becomes:

$$g = \frac{h}{3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Let the trapezoid be changed to a triangle, with the apex up, as in Fig. 5. Then $b' = 0$, and the general formula becomes:

$$g = \frac{h^2 b + 2 h d b}{4 h b + 6 d b}$$

$$g = \frac{h}{2}\left(\frac{h + 2 d}{2 h + 3 d}\right) \quad . \quad . \quad . \quad . \quad (14)$$

If $d = 0$:

$$g = \frac{h}{4} \quad . \quad . \quad . \quad (14 \text{ bis}).$$

If the figure be a triangle with the base up, as in Fig. 6, then $b = 0$, and the height, g, above the apex of the triangle is:

$$g = \frac{h^2 b' + 4 h d b'}{2 h b' + 6 d b'}$$

$$g = \frac{h}{2}\left(\frac{h + 4 d}{h + 3 d}\right) \quad . \quad . \quad . \quad . \quad (15)$$

If $d = 0$;

$$g = \frac{h}{2} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (16)$$

If the surface were inclined instead of vertical, all of the above formulas would give the value of g, measured along the slope. If for any purpose the vertical value of g should happen to be required, it would of course be obtainable by multiplying this value by cosine α.

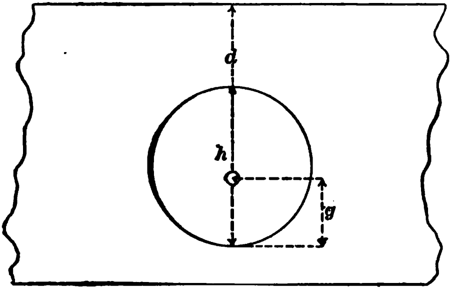

FIG. 22.

If the surface is circular, as in Fig. 22, and h = diameter of circle, then:

$$g = \frac{h}{8}\left(\frac{3h + 8d}{h + 2d}\right) \quad . \; . \; . \quad (17)$$

If $d = 0$,

$$g = \frac{3h}{8} \quad . \; . \; . \; . \; . \; . \quad (18)$$

PRACTICAL IMPORTANCE OF THE POSITION OF THE CENTRE OF PRESSURE.

14. A knowledge of the position of the centre of pressure, as determined by the preceding formulas, is necessary in all calculations relating to water pressure, as the following examples will show.

Fig. 23 represents a section through a reservoir wall, sustaining a water pressure of depth, h, equal to the height, $A\,B$, of the wall. The tendency of the water pressure is 1st, to shove the wall bodily forward, by sliding on the base, A, C, and 2d, to overturn it by rotation around the outer toe, C. The force tending to produce sliding, is that due to the total pressure, P, as determined by previous formulas; the force tending to produce rotation is that due to the pressure, *P*, multiplied by the vertical distance, *g*, of the centre of pressure above the point *C* of possible rotation. When these forces are known, the section of the wall can be so proportioned as to resist these destructive tendencies.

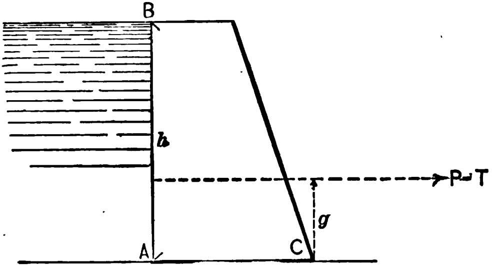

Fig. 23.

It is usual in such cases to calculate the pressures per running foot of the wall, that is, to make $b = 1$ in the preceding formulas, because the wall, of whatever length it may be, may be considered as made of a succession of 1 foot lengths, each sustaining a prism of water

1 ft. thick, so that the proper section of one of these lengths of wall would be that for the whole wall, no matter what its length.

EXAMPLE.—Referring to Fig. 23, let $h = 30$ ft. What is the pressure, P, tending to produce sliding on the base $A\ C$, and what the moment of this force. $g P$, tending to produce rotation around C, both taken per running foot of wall?

Solution.—Using formula (2), making $b = 1$, and $h = 30$, we have:

$$P = 31.25 \times 900 = 28125 \text{ lbs. } \textit{Ans.}$$

Using formula (13),

$$g = \frac{30}{3} = 10 \text{ ft.}$$

Then

$$g P = 10 \times 28125 = 281250 \text{ ft. lbs. } \textit{Ans.}$$

EXAMPLE.—Fig. 24 represents the same wall as in previous example, but in a reversed position. The batter is $\frac{1}{4}$, consequently tang. $\alpha = 0.25$, and $\alpha = 14° 02'$. Find P and $g\,T$ per running foot.

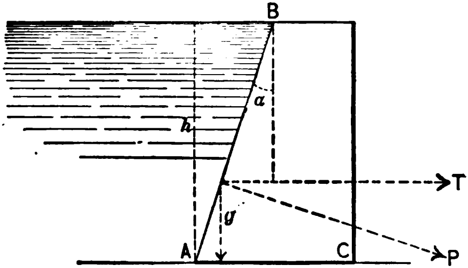

Fig. 24.

Solution.—From the data the slant height $A\,B = 30.92$ ft. Therefore, by the General Law, page 18, we find:

$$P = 30.92 \times 15 \times 62.50 = 28988 \text{ lbs.}$$

Ans.

Using formula (6), we have:

$$T = 28988 \times 0.97015 = 28123 \text{ lbs.}$$

If we did not already know P, we might use formula (8), from which b and $2\,d$ disappear, thus:

$$T = \overline{30.92}^2 \times 31.25 \times \overline{0.97015}^2 = 28012 \text{ lbs.}$$

The slight difference between these two values of T are due to neglect of small decimals.

Formula (13) gives the value of g, measured along the slant height $A\,B$. To obtain the desired vertical distance shown in Fig. 24, this value must be multiplied by cos. α, thus:

$$g = \frac{30.92}{3} \times 0.97015 = 10 \text{ ft.}$$

Therefore:

$$g\,T = 10 \times 28123 = 281230 \text{ ft. lbs. } \textit{Ans.}$$

Observe that values of T and of $g\,T$ are the same as in the preceding example. This proves that the horizontal thrust, T, tending to produce sliding, and the moment, $g\,T$, tending to produce rotation, are the same whether the surface in contact with the water be vertical or inclined. Furthermore, since a curved surface may be conceived as made up of an indefinite number of inclined planes, the above law may be extended to curved surfaces as well. This law greatly simplifies the calculation of the destructive forces exercised against the sides of reservoirs containing water.

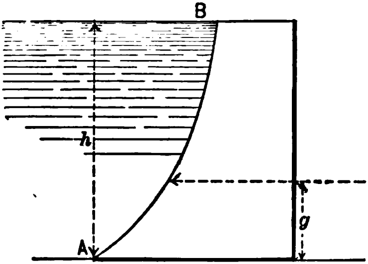

FIG. 25.

EXAMPLE.—Fig. 25 is a section through the side of a reservoir containing water to a depth $h = 45$ feet, the surface in contact with the water being a curve, circular, parabolic, elliptical or of any other form. Find T and $g\ T$ per linear foot.

Solution.—

$T = 31.25 \times 2025 = 63281$ lbs. *Ans.*

$g\ T = 15 \times 63281 = 949215$ ft. lbs. *Ans.*

We have, therefore, in all such cases as those represented by Figs. 24, 25, and 26:

$$T = 31.25\,h^2 \quad \ldots\ldots \quad (19)$$

$$g\,T = \frac{31.25\,h^3}{3} \quad \ldots\ldots \quad (20)$$

when h = vertical depth of water, and T = horizontal thrust per running foot.

SPECIAL PROBLEMS.

15. The vertical downward pressure on the sloping or curved surface shown in Figs. 24 and 25 is best obtained by calculating the area between the vertical dotted line h, drawn from the foot of the slope or curve to the surface of the water, and the surface $A\,B$ of the wall in contact with the water, and multiplying it by 62.50. The vertical downward pressure is, in all such cases, the weight of the prism of water supported by the inclined or curved surface $A\,B$ in contact with it. If this surface is vertical, as in Fig. 23, there is no downward pressure.

Fig. 26 is a section through a barrier, of plank for instance, placed across a canal and supported by two timbers, *A* and *B*, shown end on in the figure.

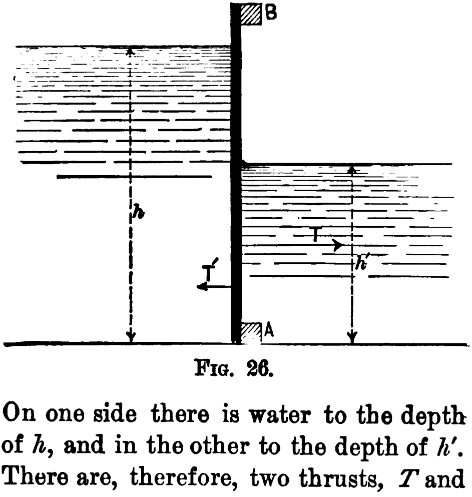

FIG. 26.

On one side there is water to the depth of h, and in the other to the depth of h'. There are, therefore, two thrusts, T and T', in opposite directions against the gate or barrier. The resultant thrust T'' (not indicated in the figure) per running foot is the difference of the two in the direction of the greater, T.

By formula (19) we would have:

$T = 31.25\, h^2$; and $T' = 31.25\, h'^2$.

Therefore:

$$T'' = T - T' = 31.25\,(h^2 - h'^2)\ .\ (21)$$

Example.—Referring to Fig. 26, let $h = 15$ ft. and $h' = 9$ ft. Find T'' per running foot:

Solution.—Inserting data in formula (21),

$$T'' = 31.25\,(225 - 81) \text{ lbs.}$$

$$T'' = 4500 \text{ lbs. } \textit{Ans.}$$

The resultant moment, $g''\,T''$, tending to produce rotation about A, is the difference between the two moments $g\,T$ and $g'\,T'$. We have, therefore, per running foot:

$$g''\,T'' = g\,T - g'\,T'.$$

Using formula (20), we have:

$$g''\,T'' = \frac{31.25}{3}\,(h^3 - h'^3)\quad .\ .\ (22)$$

Example.—In preceding example, find $g''\,T''$ per running foot.

Solution.—Using formula (22):

$$g'' \, T'' = \frac{31.25}{3}(3375 - 729) \text{ ft. lbs.}$$

$$g'' \, T'' = 27562.50 \text{ ft. lbs. } \textit{Ans.}$$

If it were desired to find the value of g'', or the point of application of T'' above A, it can be obtained in the above example, by dividing 27562.50 by T'' already calculated. The general formula for g'' may be derived by dividing formula (22) by formula (21). Thus:

$$\frac{g'' \, T''}{T''} = \frac{\frac{31.25}{3}(h^3 - h'^3)}{31.25\,(h^2 - h'^2)}$$

$$g'' = \frac{1}{3}\left(\frac{h^3 - h'^3}{h^2 - h'^2}\right) \quad . \; . \; . \quad (23)$$

EXAMPLE.—With the previous data, find g''.

Solution.—Inserting data in formula (23):

$$g'' = \frac{1}{3}\left(\frac{3375 - 729}{225 - 81}\right)$$

$$g'' = 6.125 \text{ ft. } \textit{Ans.}$$

Knowing the values of g'' and T'', it is easy to find the pressure upon the two supports A and B, per running foot.

Thus, the moment $g''\ T''$ tends to produce rotation of the gate around the point A. It is prevented from rotating by the pressure, or reaction, W, of the upper support, B, acting with the lever arm $A\,B$. We have therefore:

$$W \times A\,B = g''\ T''$$

$$W = \frac{g''\ T''}{A\,B} \quad . \ . \ . \ . \ . \quad (24)$$

The pressure, W', upon the lower support, A, may be found by subtracting W from T'', since the whole weight is divided between the two, or it may be found independently in the same way as W. Thus, T'' acting with the lever arm $A\,B - g''$ tends to produce rotation around the upper support B. The tendency is resisted by the reaction, W', of the lower support A, multiplied by the lever arm $A\,B$. Hence:

$$W' = \frac{T'' \, (A\,B - g'')}{A\,B} \quad . \; . \; (25)$$

Example.—With the previous data, and letting $A\,B = 17$ ft., find the pressure upon A and B.

Note.—Owing to uncertainty as to exact points of bearing, the distance $A\,B$ is taken from out to out of the supports.

Solution.—Using formula (24), the pressure, W, upon the upper support B is:

$$W = \frac{27562.50}{17}$$

$$W = 1621.32 \text{ lbs. } \textit{Ans.}$$

That on the lower support, A, is:

$$W' = \frac{4500\,(17 - 6.125)}{17}$$

$$W' = 2878.68 \text{ lbs. } \textit{Ans.}$$

Proof.—$W + W' = T''$

$$2878.68 + 1621.32 = 4500 \text{ lbs.}$$

All of the values obtained in the preceding series of examples are per running foot. To obtain total pressures, they must be multiplied by the length, or breadth, of the piece undergoing the pressure.

EXAMPLE.—In preceding example, let the breadth, b, of the gate be 10 ft. Find total pressure, P, against it.

Solution.—$P = b\,T''$

$P = 10 \times 4500 = 45000$ lbs. *Ans.*

EXAMPLE.—Let the length of the upper support, B, be 10 ft., as in previous examples, find total equally distributed pressure, P, upon it.

$P = 10\,W$

$P = 10 \times 1621.32 = 16213.2$ lbs. *Ans.*

This gives a maximum bending stress at the middle of the beam of 20266 lbs.

A rather complicated example will now be given, calculated to bring out some of the most difficult points in hydrostatics.

Example.—Fig. 27 shows, in vertical section, a conduit, *C*, through the side of a reservoir, closed by a trapezoidal gate, *G*, hung upon a shaft at its upper side. The side of the wall next the water has an inclination of 30° with the vertical. The dimensions of the gate are shown in feet on the figures, and are

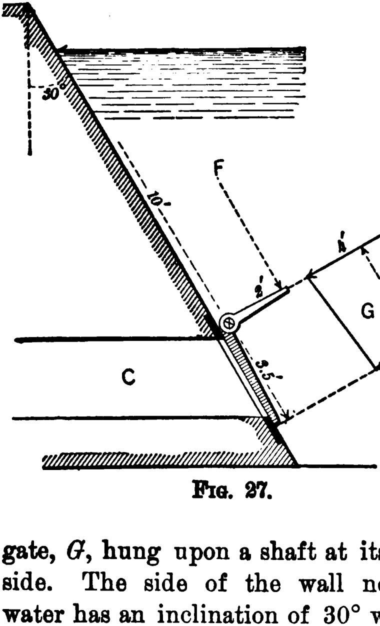

Fig. 27.

taken on the slant height, as shown. There is a projecting crank 2 ft. long, by pulling upon which the gate may be raised. It is desired to find the force, F, acting at right angles to the crank, necessary to start the gate against its own weight, 300 lbs., and the pressure of the water against it.

Solution.—Let us first determine the water pressure, P, and for this we will use the General Law, page 18.

The area of the gate, from the data, is 12.25 sq. ft. Its centre of gravity, by well-known rule, is at the distance of 1.67 ft. from its upper side. The distance of centre of gravity below the surface of the water, on the slant height, is therefore $10 + 1.67 = 11.67$ ft. The vertical distance is equal to the slant distance multiplied by the cosine of the angle of slope, 30°, which is 0.866. The vertical depth of the centre of gravity of the gate below the surface of the water is, therefore, $11.67 \times 0.866 = 10.11$. Hence,

$$P = 12.25 \times 10.11 \times 62.50 = 7740 \text{ lbs.}$$

We now require the centre of pressure, or point of application of P. For this we use formula (11), in which we have, from the data, $h = 3.5$, $b = 3$, $b' = 4$, $d = 10$, all on the slant height; then to find g, the distance of centre of pressure from lower side of the gate, also on the slant:

$$g = \frac{3.5 \times 3.5\,(3+4) + 2 \times 35\,(3+8)}{7\,(6+4) + 60\,(3+4)}$$

$$g = 1.75 \text{ ft.}$$

The distance from the hinge or axis of rotation is therefore $3.50 - 1.75 = 1.75$ ft., and the moment of the pressure about this point is:

$$g\,P = 1.75 \times 7740 = 13545 \text{ ft. lbs.}$$

The component of the weight of the gate at right angles to its plane is

$$W \sin. 30^\circ = 300 \times 0.50 = 150 \text{ lbs.}$$

It acts at the centre of gravity of the gate, or at the distance of 1.67 ft.

from the hinge. The moment is therefore:

$$150 \times 1.67 = 250.50 \text{ ft. lbs.}$$

The total moment of resistance of the gate is therefore

$$13545 + 250.50 = 13795.50 \text{ ft. lbs.}$$

The necessary force, F, to start the gate, working with a lever arm of 2 ft. is therefore:

$$F = \frac{13795.50}{2} = 6897.75 \text{ lbs. } \textit{Ans.}$$

The arrangement shown in Fig. 27 is one almost impossible to be met with in practice, but has been assumed as introducing a number of conditions which increase the usefulness of the example as an exercise,

Such a conduit as shown would generally, in practice, be either circular or rectangular in cross-section, and the gate in any case would generally be rectangular and of the sliding type, raised and lowered with a screw. In such a case the resistance to be overcome would be the pressure, P, multiplied by the coefficient of friction, which might be about 0.75.

EXAMPLES FOR PRACTICE.

1. The side of a receptacle containing water is inclined at an angle of 12° 30′ to the vertical. A trapezoidal opening is made in it, as in Fig. 21, of which the upper parallel side is 5 ft. long, the lower one 7 ft., and the height 8 ft. The upper side of the trapezoid is 18 ft. below the surface of the water, measurements taken on the slope. If the opening were closed by a gate, at what distance below the surface of the water, measured vertically, will the centre of pressure upon the gate be?

21.10 ft. *Ans.*

2. A triangular surface is marked out on the vertical side of a receptacle filled with water. The base, 6 ft. long, is level with the surface of the water, and the height is 9 ft. At what height above the apex of the triangle is the centre of pressure?

4.5 ft. *Ans.*

3. A circular plate, 5 ft. in diameter, is set in the vertical side of a receptacle containing water. The centre of the circle is 4 ft. below the surface of the water. What is the pressure, P, against the circle, and how far below its centre is the centre of pressure?

$P = 4908.75$ lbs. *Ans.*
0.39 ft. *Ans.*

4. A trapezoidal dam, shown in section in Fig. 23, sustains a water pressure against the vertical face of 57 ft. What is the horizontal thrust, T, tending to push it forward on its base, and what the moment, $g\ T$, tending to overturn it, both per linear foot?

$T = P = 101531.25$ lbs. *Ans.*
$g\ T = 1929093.75$ ft. lbs. *Ans.*

5. A trapezoidal dam, as shown in Fig. 24, sustains pressure due to a head of 60 ft. against a face having a batter of 1 in 6. What is the pressure P against the sloping face, and what are its horizontal and vertical components, T and V? also, what is the overturning moment, $g\ T$, all per running foot?

$$\left.\begin{aligned} P &= 114000 \text{ lbs.} \\ T &= 112500 \text{ lbs.} \\ V &= 18750 \text{ lbs.} \\ gT &= 2250000 \text{ ft. lbs.} \end{aligned}\right\} \textit{Ans.}$$

6. Referring to Fig. 25, let the curved surface, $A\ B$, in contact with the water, be half the arc of a circle of which the half chord, $h = 15$ ft., and the versed sine $= 5$ ft. Find V, T and $g\ T$, per running foot.

$$\left.\begin{aligned} V &= 3193.75 \text{ lbs.} \\ T &= 7031.25 \text{ lbs.} \\ g\ T &= 35156.25 \text{ ft. lbs.} \end{aligned}\right\} \textit{Ans.}$$

7. Referring to Fig. 26, let $h = 21$ ft., and $h' = 12$ ft. Find the resultant thrust, T'', its centre of pressure, g'', and moment, $g''\,T''$, per running foot.

$$\left.\begin{aligned} T'' &= 9281.25 \text{ lbs.} \\ g'' &= 8.45 \text{ ft.} \\ g''\,T'' &= 78427 \text{ ft. lbs.} \end{aligned}\right\} \textit{Ans.}$$

8. If in above example let $A\,B = 24$ ft., and the length of the upper support, B, $= 9$ ft. What evenly distributed pressure is upon it?

29410 lbs. *Ans.*

SPECIFIC GRAVITY.

GENERAL PRINCIPLES.

16. The specific gravity of a body is the ratio of its weight to that of an equal volume of distilled water at 60° Fahr.

Thus, if a cubic foot of any substance weighs twice as much as a cubic foot of water, its specific gravity is 2.

Water is taken as the standard of comparison on account of its availability, its uniform weight under easily secured conditions and the facility with which it can be applied to processes of determination.

There are several ways by which this ratio may be determined. If a sample of the substance be wrought into some regular shape, a cube for instance, its volume may be accurately measured and its weight ascertained. The weight of an equal volume of water is readily calculated, and by dividing the weight of the substance by the weight of the water its specific gravity is known.

Example. — A parallelopipedon of metal weighs 18.77 lbs. and measures 6″ × 4″ × 3″ and contains therefore 72 cubic inches = $\frac{1}{24}$ cu. ft. The same volume of water will weigh $\frac{62.5}{24} = 2.604$ lbs. Therefore:

$$\text{sp. gr.} = \frac{18.77}{2.604} = 7.21.$$

Example.—A block of wood is in the form of a cube, 6 inches on the side, and weighs 5 lbs. It contains 216 cu. in. = $\frac{1}{8}$ cu. ft. The weight of an equal volume of water is $\frac{62.5}{8} = 7.81$ lbs. Therefore:

$$\text{sp. gr.} = \frac{5}{7.81} = 0.64. \ \textit{Ans.}$$

But it would be generally inconvenient and frequently impossible to measure the exact cubic contents of a piece of material of which we wish to ascertain the specific gravity. In the case of an irregularly shaped piece, we might employ an indirect method of measurement. We might take a vessel of proper size and shape partly filled with water, and carefully note the exact level at which the water stood in it. Then, having previously weighed the piece, we might immerse it in the water, either by its own weight, or if too light to sink, by gently pressing it down until it was completely submerged. It would then displace a volume of water equal to its own bulk, and correspondingly raise the level of the water in the vessel. By measuring the difference between the two levels, the volume of the piece can be calculated.

EXAMPLE.—Into a vessel with vertical sides and cross-section of 144 sq. in. an irregularly shaped fragment of rock crystal is plunged, raising the water level $\frac{5}{16}$ths of an inch. What is the volume of the piece?

Solution.—

$$\frac{5}{16} \times 144 = 45 \text{ cu. in.} = \frac{1}{38.40} \text{ cu. ft.}$$

Ans.

Knowing the weight and volume of the piece, its specific gravity can be calculated as in the previous examples.

From what precedes, we see that whatever the size, shape or weight of a solid body may be, its specific gravity is equal to its own weight divided by that of an equal volume of water. Expressed as a formula, we have:

$$S = \frac{W}{D} \quad \ldots\ldots \quad (26)$$

in which $S =$ specific gravity, $W =$ weight of piece, and $D =$ weight of an equal volume of water.

It is evident that if any two of the above factors are known, the third may be ascertained. Thus:

$$W = SD \quad \ldots\ldots \quad (27)$$

$$D = \frac{W}{S}. \quad \ldots\ldots \quad (28)$$

LAW OF ARCHIMEDES.

17. A general and very accurate method of determination is afforded by the application of the Law of Archimedes, which may be thus stated:

When a solid body is immersed in water, it loses a portion of its weight equal to that of the volume of water which it displaces.

If, therefore, we could determine how much of its weight the body lost by being immersed, we should know the weight of an equal volume of water, because when submerged it displaces its own bulk.

The desired information is obtained by the very simple expedient of first weighing the body in the air in the usual way, and secondly, by means of a proper arrangement of scales weighing it in water. This latter weighing will be less than the former, because the weight of the body is partly supported by the water, and the difference between the two weights represents the amount lost by the body by immersion. But by Archimedes's law as above stated, this loss is equal to the weight of the volume of water displaced, and as the body has displaced its own volume, the loss of weight is equal to the weight of a volume of water equal to the volume of the body.

Therefore if $W =$ weight of the body in air, and $W' =$ its weight in water, then in formula (26), $D = W - W'$, and we have:

$$S = \frac{W}{W - W'} \cdot \cdot \cdot \cdot \cdot \quad (29)$$

Two cases present themselves. First, when the body is heavier than water, and therefore sinks in it by its own weight. In this case (29) applies.

Example. — An irregularly shaped piece of metal weighs 7.50 lbs. in the air and 6.46 lbs. in water. What is its specific gravity?

Solution.—

$$S = \frac{7.50}{7.50 - 6.46} = \frac{7.50}{1.04} = 7.21.$$

Ans.

The second case occurs when the body is lighter than the water, and would therefore float upon it. In order to submerge it, a weight sufficient to sink it must be attached. What we want to know is the weight of water displaced by the light body when submerged, for we can then determine its specific gravity by formula (26). The following considerations enable us to do this: It is evident that the weight of water displaced by the two bodies when sunk together must be equal to the sum of the weights displaced by each if sunk separately, supposing that it were possible for the lighter body to sink by itself. Now we have two expressions for the weight of this displacement, one applicable to the light body, given by (26), and the other $W - W'$, derived from (29), applicable to the heavy body and the combination of the two.

The data required, therefore, are: W = weight of light body in air of which the specific gravity is required; H = weight in air of the sinker; H' = weight in water of the sinker; W' = weight in water of light body and sinker combined.

These data having been obtained, we have:

$\frac{W}{S}$ = weight of water displaced by light body.

$H - H'$ = weight of water displaced by sinker.

$W + H - W'$ = weight of water displaced by sinker and body.

Then:

$$\frac{W}{S} + H - H' = W + H - W'$$

$$\frac{W}{S} = W - W' + H'$$

$$S = \frac{W}{W - W' + H'} \quad . \ . \ (30)$$

Example.—A piece of cork weighs $\frac{1}{2}$ oz. in air. A piece of lead weighing 4 oz. in air and 3.64 oz. in water is attached to the cork as a sinker. The weight in water of the combination is 2.04 oz. What is the value of S?

Solution.—Substituting in (30), we have:

$$S = \frac{0.50}{0.50 - 2.04 + 3.64}$$

$$= \frac{0.50}{2.10} = 0.238. \textit{ Ans.}$$

The discovery by Archimedes of the law known by his name, and the earliest application of it by him to a practical use, were made simultaneously, according to an accredited tradition. Viturius tells us that King Hero of Syracuse gave 7465 grammes of gold to a goldsmith to be made into a crown. When the crown was finished, although the weight was correct, Hero suspected that in its manufacture a certain portion of silver had been substituted for an equal weight of gold. He therefore consulted Archimedes, and entrusted to him the duty of discovering the fraud without injury to the crown. The task seemed hopeless, but while in the bath Archimedes noticed, apparently for the first time, the phenomenon of the displacement of water by the immersion in it of a solid body. As the bearing of this discovery on the proposed problem flashed upon him, and doubtless realizing its far-reaching scope in further scientific research, we are told that, beside himself with exultation, he sprang from the bath, and all unclothed, rushed through the streets of Syracuse exclaiming "Eureka! Eureka! I have found it! I have found it!"

The practical application of the principle was as follows: A piece of gold when weighed in air and water, was found to lose 0.052 of its weight by immersion. A piece of silver was found to lose 0.095 of its weight when immersed. The crown was found to lose 467 grammes in water.

Having these data, the problem which

at first baffled even the skill of Archimedes became a matter of elementary algebra, and is given as such in the introductory chapter of Briot's Algebra.

Let $x =$ weight of silver in the crown. Then $7465 - x =$ weight of gold in it. The weight of water displaced by x grammes of silver will be:

$$0.095\,x$$

and by the gold

$$0.052\,(7465 - x).$$

The water displaced by the crown, made up of x grammes of silver and $(7465 - x)$ grammes of gold, weighs 467 grammes. Then:

$$0.095\,x + 0.052\,(7465 - x) = 467.$$

Whence:

$x = 1833$ grammes $=$ weight of silver.

and

$7465 - x = 5632$ grammes $=$ weight of gold.

The solution was no doubt approximate only, because the specific gravity of the test pieces might be different from that of the gold and silver used in the crown, and it was assumed that the two metals underwent no change of volume by the alloying, but it would be difficult to find in the whole history of scientific investigation a more brilliant triumph of genius than is offered by the above problem and its solution.

SPECIAL APPLICATIONS OF THE LAW OF ARCHIMEDES.

18. A useful corollary to the Law of Archimedes is as follows:

A buoyant body floating in water displaces an amount of water equal to its own weight.

EXAMPLE.—For the purpose of observing the velocity of a tidal current, it is desired to ballast a piece of joist, 10 ft. long by 4 in. square, so that it will float upright, leaving 3 in. of its length out of water. The ballast will consist of pieces of lead fastened to one end of the joist, and the volume of the lead, being relatively insignificant, will be ignored. What should be the combined weight of joist and ballast in order that it may float as desired?

Solution.—As $g' g''$ of the joist are to be submerged, and the cross-section of the piece is $4'' \times 4'' = 16''$, the volume of the submerged portion is 1872 cu. in. = 1.083 cu. ft. The float will therefore displace this volume of sea water, of density = 64 lbs. per cu. ft., weighing $1.083 \times 64 = 69.31$ lbs. *Ans.*

If the stick were of white pine it would require about 40 lbs. of ballast. It should be well painted to prevent increase of weight by absorption of water.

EXAMPLE.—A barge loaded with coal has been sunk in tidal water, the barge and cargo weighing 650 tons or 1300000 lbs. It is desired to raise it by means of water-tight caissons attached to it at low water, in order that the rising tide may lift it so that it can be towed into shallower water, the operation being repeated on successive tides until the wreck is finally beached. The caissons are cylindrical in shape, of 12 ft. diameter, and weigh 2000 lbs. per running foot. The buoyancy of the vessel is not taken into account, as it is supposed to not more than offset the adhesion of the mud in which it has settled. The caissons may be submerged for 90% of their bulk. How many running feet of such caissons will be required to float the barge?

Solution.—Let x = the length of caissons. Since it weighs 2000 lbs. per foot and the wreck weighs 1300000 lbs., the total weight to be floated is $2000x + 1300000$. To float this weight the caissons must displace an equal weight of sea water at 64 lbs. per cubic foot. Then, recollecting that only 90% of their bulk is available, we have:

$$113 \times 64 \times 0.90\, x = 2000\, x + 1300000.$$
$$x = 288 \text{ ft. } \textit{Ans.}$$

It may be convenient sometimes to know the volume of a body of certain weight and specific gravity. From previous formulas we deduce:

$$V = \frac{W}{62.5\, S} = \frac{0.016\, W}{S} \quad . \; . \quad (31)$$

$$V = \frac{D}{62.5} = 0.016\, D \quad . \; . \; . \; . \quad (32)$$

in which $V =$ volume of body in cu. ft., $W =$ weight in lbs., and $D =$ weight of displaced water.

Example.—What volume of cork, specific gravity 0.24, must be attached to 6 lbs. of iron, specific gravity 7.6, in order that the whole may just float in water? (*Bowser.*)

Solution.—In this problem we want to know the volumes and weights of cork and iron. Referring to (31), we have:

Weight of iron . . . . 6 lbs.

Volume of iron $\dfrac{6}{62.5 \times 7.6}$ cu. ft.

Weight of cork . . . . x lbs.

Volume of cork $\dfrac{x}{62.5 \times 0.24}$ cu. ft.

The volumes of cork and iron multiplied by 62.5 must equal their combined weights. Then:

$$\frac{6}{7.6} + \frac{x}{0.24} = 6 + x$$

$$x = \frac{9.504}{5.776} \text{ lbs.}$$

This is the weight of the cork. From (31), we have for the volume:

$$V = \frac{0.016}{0.24} \times \frac{9.504}{5.776}$$

$$= 0.1097 \text{ cu. ft. } \textit{Ans.}$$

GENERAL LAW OF BUOYANCY.

19. In all problems relating to buoyancy and flotation, the general rule is that the immersed volume in cubic feet of the floating body or bodies, multiplied by 62.5 (or whatever the weight of the liquid may be), must be equal to or greater than the weight in pounds of the body or bodies.

Formulas (32) and (33) enable us to determine the volume of solids of which we know the weight, specific gravity, or weight of water displaced by them.

Example.—A cast-iron cannon ball weighs 32.24 lbs. What is its volume?

Solution.—Assuming $S = 7.20$ lbs., we have, using (31):

$$V = \frac{0.016 \times 32.24}{7.2} = 0.0716 \text{ cu. ft. } \textit{Ans.}$$

Results thus obtained are necessarily approximate, because though 7.2 is given as an average value, the specific gravity of any given specimen may readily vary. A surer though very much more complicated method is to ascertain by actual trial the weight of displaced water by weighing the given specimen in air and water, and applying formula (32).

EXAMPLE.—A heavy body of irregular shape is found to weigh 30 lbs. in air and 23 lbs. in distilled water of 60° Fahr. What is its volume?

Solution.—

$$V = \frac{7}{62.5} = 0.112 \text{ cu. ft. } \textit{Ans.}$$

The specific gravity of the substance is ascertained from the same data, and is 4.286, about half the weight of an equal volume of copper.

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